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Design of a miniaturized spiral antenna for partial discharge detection system

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Abstract

A miniaturized spiral antenna with a broadband balun for a partial discharge (PD) localization system is proposed. The proposed antenna has broadband characteristic from 925 MHz to 1.6 GHz and a unidirectional radiation pattern. The overall dimensions of the fabricated antenna are $80 \times 80 \times 40$ mm^3, which is the smallest size among antennas for the PD detection system. The measured −10 dB reflection bandwidth starts at 925 MHz, and the measured directivity of the antenna is about 6 dB in the frequency band.

KEYWORDS

3D-printed components, cavity-backed antenna, flush mountable antenna, UAV, UWB antenna

1 | INTRODUCTION

In the power transfer system including power transformers and gas-insulated switchgears, partial discharge (PD) causes a major failure of the entire system. To prevent the major failure, PD detection by sensing UHF signal has been applied.[1–6] Since one or more antennas are used as UHF signal sensors that dominate overall performance of the PD detection system, the design of UHF signal sensing antennas is crucial. The antenna should have a broadband characteristic to prevent UHF signal distortion and a unidirectional

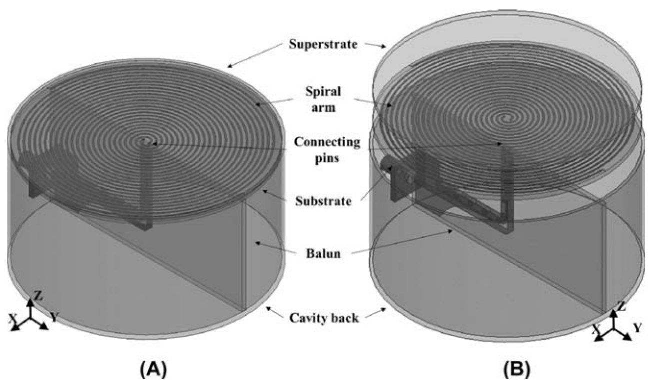

FIGURE 1 Perspective views of the proposed antenna. A, Assembled antenna. B, Disassembled antenna

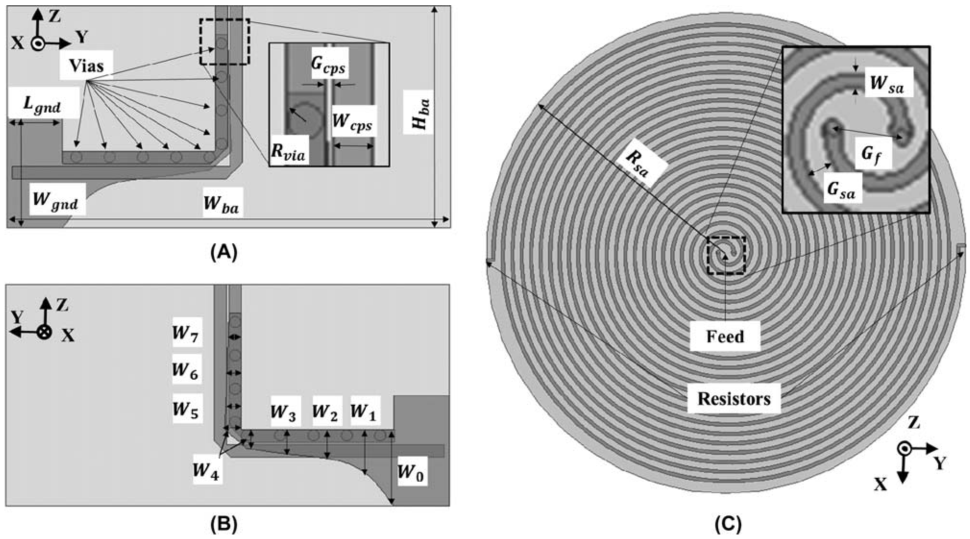

FIGURE 2 Design of the balun and the spiral antenna. A, Top view of the balun. B, Bottom view of the balun. C, Top view of the spiral antenna

radiation pattern to detect UHF signal sensitively.[1] In addition, the antenna is required to be small since the size of mountable spots, including a flushing pipe and a monitoring window, is limited in the power system. In previous broadband antenna researches, spiral antennas, microstrip patch antennas, Vivaldi antennas, and monopole antennas have been used.[1–6] However, those antennas are too large or have a narrow frequency band. A cavity-backed Archimedean antenna generally has a broadband and unidirectional radiation pattern, which is desirable properties as the PD detection sensor, but the size of a conventional spiral antenna[1,7] is hard to be miniaturized. In this work, a miniaturized cavity-backed Archimedean spiral antenna is proposed. The proposed antenna is miniaturized by applying resistors, superstrate, and broadband balun. The proposed antenna has the dimensions of 0.26 λ × 0.26 λ × 0.13 λ, which is the most compact among PD antennas. The design and optimisation of the antenna are performed using Ansoft HFSS in conjunction with quasi-Newton optimization.

2 | ANTENNA DESIGN

Figure 1 shows a perspective views of the proposed antenna. Spiral arms are printed on the substrate and covered with the superstrate. It is worthy of note that a superstrate, a balun, and a cavity back are employed for miniaturization, for impedance matching, and for guiding radiation pattern in the forward direction, respectively. The cavity back is made of aluminium, and the substrate, the superstrate, and the balun are made on 1.6 mm-thickness FR4 boards ($\varepsilon_r = 4$). The schematic of the spiral arms and the balun is shown in Figure 2. The balun is designed to transform the transmission line type from a microstrip line to a coplanar strip line (CPS), and to transform the characteristic impedance from 50 to 100 Ω with the Klopfenstein profile.[8] As shown in Figure 2A,B, ground widths at the 7 points (W_1,. . .,W_7) that are initially chosen to transform characteristic impedance between microstrip line and CPS in the Klopfenstein profile and curved line segments between the seven points are obtained by spline interpolation instead of linear segments. In addition, the balun is bent to reduce the height of the antenna. With regard to designing the spiral arms, the profile of the arms in Figure 2C is shaped in Archimedean spiral model since an Archimedean spiral antenna has a lower resonance frequency than that of a log spiral antenna. The each spiral arm is terminated with a 100 Ω resistor to eliminate internal reflections. However, the bent part of the balun and connecting pins (see Figure 1) consequently result in a discontinuity in the impedance transition. To solve the discontinuity, quasi-Newton optimization is applied. For the optimization, the ground widths at the 7 points (W_1,. . ., W_7), the gap of CPS lines (G_{cps}), the width of CPS lines (W_{cps}), and the width of the spiral arm (W_{sa}) are set as variables, where the initial values of the variables follow the Klopfenstein profile. A cost function for the optimization is then defined as

$$\text{cost}=\sum_{f}^{f_h}\left(\max\left[0, S_{11}(f)-S_{11\text{obj}}\right]\right)^2 \quad (1)$$

where S_{11} (f) is the reflection coefficient at frequency f and $S_{11\text{obj}}$ is the objective reflection coefficient (–10 dB). As a

TABLE 1 The optimized design parameters for the proposed antenna

W_{ba}	H_{ba}	L_{gnd}	W_{gnd}	G_{cps}	W_{cps}	R_{via}	R_{as}	W_{as}
80	40	10	20	0.45	2.26	1	40	0.55
Gf	W_0	W_1	W_2	W_3	W_4	W_5	W_6	W_7
2.6	13.84	8.02	5.24	4.42	3.35	2.75	2.58	2.45

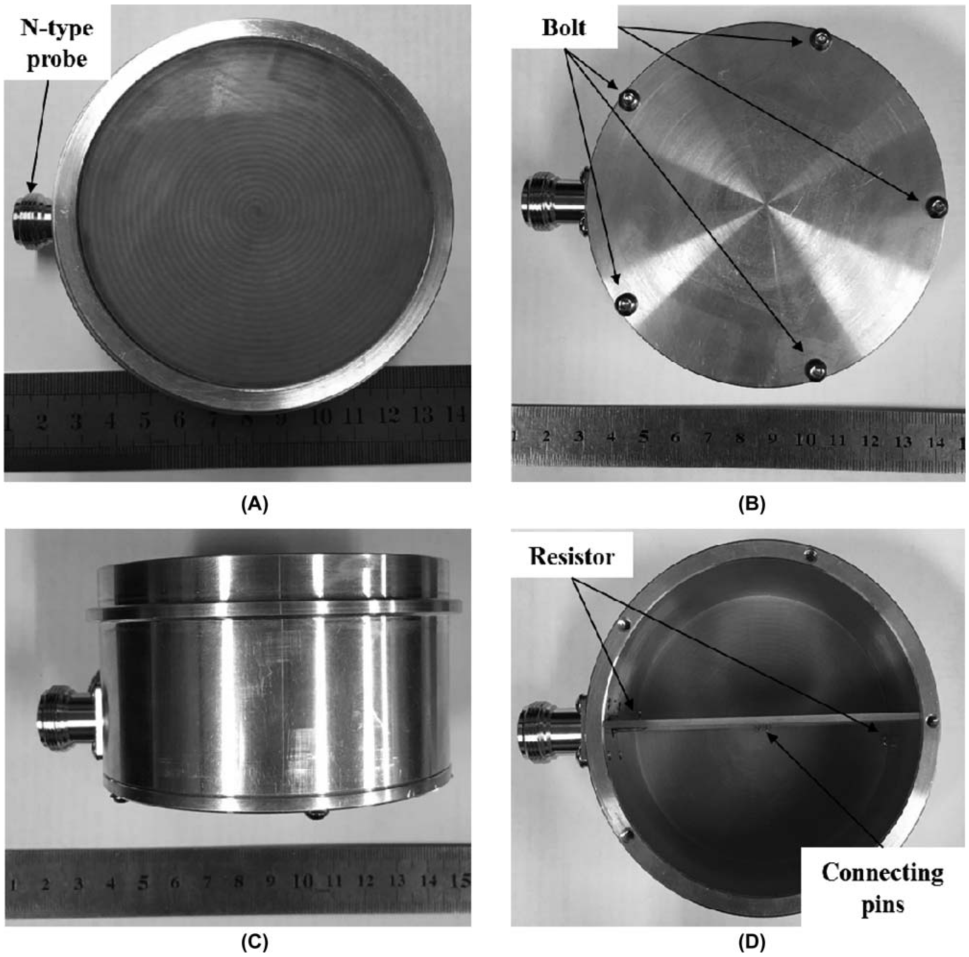

FIGURE 3 Fabricated the proposed antenna. A, Top view. B, Bottom view. C, Side view. D, Internal view

result, the optimized antenna design parameters are obtained and shown in Table 1.

3 | FABRICATION AND MEASUREMENT

Figure 3 shows the photographs of the fabricated antenna. The N-type 50 Ω connector is used as a feeder, and the 100 Ω resistors are implanted on the bottom side of the substrate. Figure 4 plots the simulated and measured $|S_{11}|$. The measured data is in good agreement with the simulated data. The matching bandwidth ($|S_{11}| < -10$ dB) of the proposed antenna in Figure 4 is from 925 MHz to frequencies higher than 1.6 GHz. Figure 5 illustrates the measured directivity of the proposed antenna. The measured directivity has a unidirectional radiation pattern and the directivity is around 6 dB in the entire frequency band. In addition, Table 2 shows the comparison between the previous PD antennas and the proposed PD antenna. Regarding to the comparison of the longest length, both physical and electrical sizes are compared. Here,

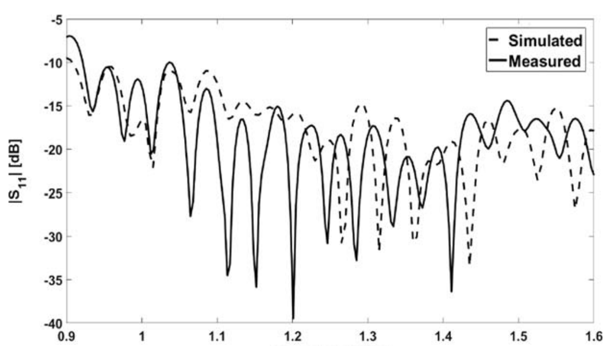

FIGURE 4 Simulated and measured $|S_{11}|$ of the proposed antenna

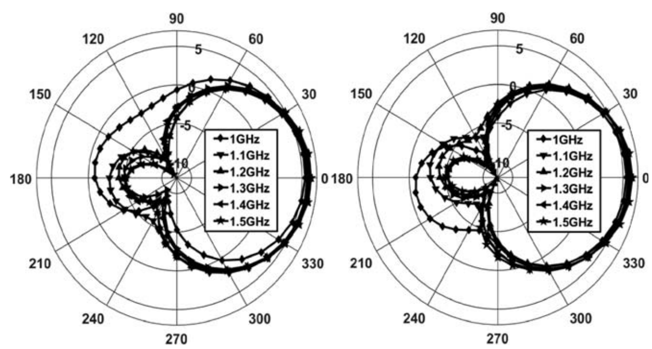

FIGURE 5 Measured directivity of the proposed antenna. A, *x-z* plane. B, *y-z* plane

TABLE 2 Comparison of size and the lowest frequency between previous PD antennas and the proposed antenna

Ref.	Antenna type	Lowest frequency (MHz)	Longest length (mm)	Longest length (λ_l)	Radiation pattern
[1]	Archimedean spiral	500	191	0.318	Unidirectional
[2]	Microstrip patch	340	340	0.385	Unidirectional
[3]	Log spiral	700	220	0.51	Unidirectional
[4]	UWB dipole	1300	77	0.33	Omnidirectional
[5]	Disc loaded monopole	400	207	0.277	Omnidirectional
[6]	Vivaldi	600	38	0.76	Unidirectional
Proposed	Archimedean spiral	925	80	0.246	Unidirectional

the electrical size is normalized by the wavelength at the lowest operating frequency. As shown in Table 2, the proposed antenna has the smallest electrical size.

4 | CONCLUSION

In this work, a miniaturized cavity-backed spiral antenna is proposed. The proposed antenna has the smallest size among the referenced articles. In addition, the proposed antenna has a unidirectional radiation pattern and broadband resonance characteristic. Furthermore, the measured matching bandwidth ($|S_{11}| < -10$ dB) covers the required frequency band (from 1 to 1.5 GHz). The results demonstrate that the proposed antenna is suitable for PD detection systems and can be applied to many other applications where the broadband characteristic is essential.[9,10]

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